

Slit function measurements of an imaging spectrograph using Fourier transform techniques

Hongwoo Park^{*a}, Bruce Swinyard^b, Peter Jakobsen^c, S. Harvey Moseley^a, Matthew Greenhouse^a

^aNASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA

^bRutherford Appleton Laboratory, Chilton, Didcot, Oxon OX110QX, U. K.

^cEuropean Space Agency ESTEC, Noordwijk, 2200 AG, The Netherlands

ABSTRACT

Knowledge of a spectrograph slit function is necessary to interpret unresolved lines and spectral features in an observed spectrum. In a scanning spectrometer with a single exit slit, the slit function is easily measured by illuminating the entrance slit with a broadband source and scanning the dispersive element. In a fixed grating/or disperser spectrograph, the slit functions have been measured by illuminating the entrance slit with a monochromatic light using a pre-monochromator or a tunable laser and by varying the wavelength of the incident light. Generally these techniques are very expensive, complex or subject to a poor signal-to-noise ratio so that an accurate measurement is often not possible. Also it would be very laborious and prohibitive to an imaging spectrograph or a multi-object spectrograph that has many sets of entrance and exit slit equivalents. We explore an alternative technique that is manageable for the measurements and where the measurement is not limited by the available signal. In the proposed technique, a Fourier Transform Spectrometer (FTS) is used instead of a pre-monochromator with variable wavelengths in the conventional techniques. This approach can be extended to the visible and ultraviolet (UV) wavelength range and to imaging spectrographs and multi-object spectrograph where multiple entrance slits and multiple exit slit equivalents (detectors) produce numerous different slit functions. In this approach, the advantages of FTS are fully utilized for available signals and the computer-assisted nature of FTS makes the data processing of the measurements manageable.

Keywords: Slit Function, Spectrograph, Fourier Transform Spectrometer, Imaging Spectrometer

1. INTRODUCTION

To interpret an observed spectrum, the bandwidth of the spectrometer, which is used to measure the spectrum, has to be known. Due to the finite resolution of the measuring device, the original spectrum is smeared. In a spectrometer, the entrance and exit slits determine the spectral bandwidth, which is commonly called a slit function because it is determined mainly by the slits. The slit function is especially important to interpret unresolved lines and spectral features, like molecular band emissions and absorptions, where the spectrum varies significantly within the width of the slit function.

The slit function of a spectrometer, which is used for the data interpretation, has been obtained from a theoretical prediction or measurements. Often the slit function of a spectrometer is inferred from the dispersion characteristic at the exit plane. In a scanning spectrometer with an entrance and an exit slit, the slit function is measured from the detector output by scanning the dispersing element, either grating or prism. In a fixed grating spectrometer, the measurement of the slit function is made by illuminating a monochromatic light onto the entrance slit and by varying the wavelength of the incident light. Conventionally a variable wavelength near monochromatic source is obtained from a combination of a pre-monochromator and a broadband light source. The spectral bandwidth of the near monochromatic source has to be far narrower than the width of the slit function of the spectrometer to be measured. To obtain a very narrow spectral source from the pre-monochromator, the entrance slit has to be narrow. The output flux from the pre-monochromator is limited by the narrow size of the entrance slit and a narrow spectral width of the broadband input source. Because of the low flux of the near monochromatic light, the measurement of the slit function with this technique suffers from a low signal-to-noise ratio. The slit function measured by this method is a convolution of the true slit function with the slit function of the pre-monochromator because the slits of the pre-monochromator have a finite width. A light source stimulus has been reported for the slit function measurement of Ozone Monitoring Instrument (OMI) in the NASA Earth Observing System (EOS) Aura satellite¹. In this stimulus, an Echelle grating was used to produce multi-monochromatic lines with high grating order numbers. Because of the use of multi-spectral lines, the number of the scanning steps could

have been reduced significantly. Upon the availability of the tunable lasers, a new technique has been developed where a monochromatic source is obtained with a tunable laser. Generally the wavelength range of a single tunable laser is very limited and a separate wavelength measuring device is necessary along the tunable laser to accurately find the wavelength of the laser output. This technique has been used to determine the slit function of Total Ozone Mapping Spectrometer (TOMS) where an accurate slit function is necessary to determine effective ozone absorption cross-section accurately². This measurement was expensive, time consuming and laborious.

With the advent of array detectors, imaging spectrometer/spectrographs have become instruments of choice for many astronomical applications as well as for earth observations. It is possible that the fore-mentioned techniques can be used for the slit function measurement, but the task of measurements and data reduction may not be trivial. We propose a technique to use a Fourier Transform Spectrometer (FTS) to measure the spectrometer slit function in lieu of a pre-monochromator. In this approach, the so-called advantages of FTS are fully utilized and the measurement is not limited by the available signal. Also this approach takes advantages from the fact that FTS is tightly coupled with computer-assisted data processing. The numerous slit functions in imaging spectrograph and multi-object spectrograph from the combinations of the multi-entrance slits and the exit slit equivalents (detectors) can be managed with a relative ease.

In this paper, the terms, spectrometer and spectrograph, are interchangeably used. Historically, the term, "Spectrograph", was used for the instrument in which a spectrum was observed with a photographic plate and "Spectrometer" became in use when a photo-electrical detector was used behind the exit slit. Since an array detector resembles the function of a photographic plate by recording a range of spectrum, the term, "Spectrograph" is still used for a spectrometer with a multiple array detector.

2. SLIT FUNCTION

As stated previously, the slit function of a spectrometer is nothing but the bandpass function of the spectrometer. For a spectrometer with a perfect optics, the slit function is a convolution of the entrance slit image with the exit slit (Figure 1). The ideal spectrometer slit function, a triangular function, is obtained when the entrance slit is imaged exactly over the exit slit for a monochromatic light of the exit slit wavelength. Normally the spectrometer slits are rectangular and placed such that the slit length direction is perpendicular to the dispersion direction and thus, the slit function is expressed in one dimensional spectral dispersion coordinate. For a perfect optics case, where there are no aberrations and diffractions, the intensity distribution of the entrance slit image for a monochromatic light on the exit plane will be a boxcar function as shown in Figure 1a. The width of this boxcar function is determined by the width of the entrance slit and the position of this function is determined by the dispersion characteristic of the disperser in the spectrometer. The aperture function of the exit slit can also be expressed as a boxcar function as shown in Figure 1b. The position of the exit slit aperture function is fixed due to a physical placement of the slit, but the position of the intensity distribution function of the entrance slit varies as a function of wavelength of the incident monochromatic source (Figure 1c). The convolution of these two functions yields a triangular function for a perfect condition (Figure 1d). And a slit function is uniquely defined for a given set of entrance and exit slits. The slit function is used only in a relative sense and is normalized for the convenience of use.

In reality, the image of the entrance slit will be modified with Point Spread Function (PSF) of the spectrometer and the spectral disperser has a different dispersion power which results in a different magnification in the spectral direction. A prism has a different index of refraction for a different wavelength and a grating yields a slight different dispersion on the exit plane as a function of the cosine angle between the grating normal and the diffracted direction. Thus, the slit function deviates from the triangular function. If the width of the entrance slit image is different from that of the exit slit, the slit function becomes trapezoidal.

In a spectrograph with an array detector, each detector element functions as an exit slit. Especially in an imaging spectrograph, which has a long entrance slit to cover the spatial dimension, optics distortions and aberrations can result in not only different shapes of slit functions but also different center wavelengths for different imaging fields.

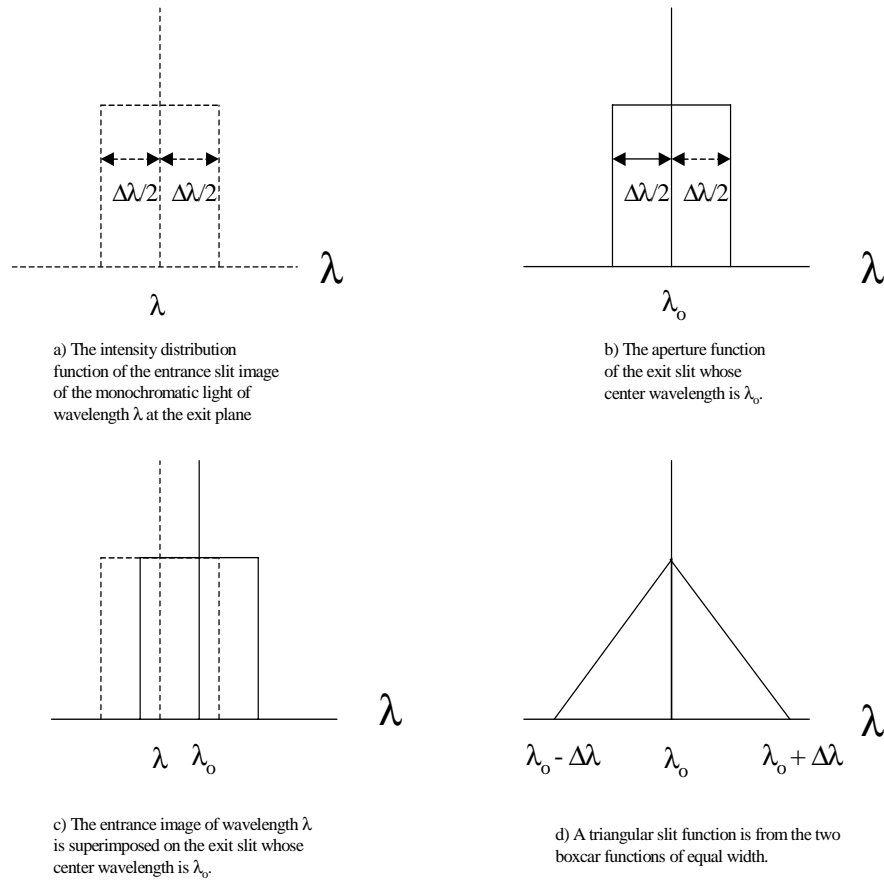


Figure 1. A pictorial description of a geometrical slit function. The vertical scale is arbitrary and the horizontal scale is in wavelength at the exit plane. The real image of the entrance slit is obtained when the boxcar function shown in a) is convolved with a Point Spread Function (PSF) of the spectrometer. When this image is convolved with the exit slit aperture function, a real slit function is produced.

3. MEASUREMENT TECHNIQUES FOR SLIT FUNCTION

In some applications, a precise knowledge of the slit function is not necessary and the spectral bandpass of a spectrometer is derived from the dispersion characteristics of the spectrometer. In other applications, the actual slit function is measured to determine the spectral resolution of the spectrometer. The slit function measurement can be used for the verification of the spectrometer optics performance. Often the measured one is necessary and required. The following reviews techniques that have been used in the past to measure the slit function.

In a scanning spectrometer which has an entrance slit and a single exit slit, the slit function is obtained from the output signal of the detector behind the exit slit by illuminating the entrance slit with a broadband source and by scanning the wavelength of the spectrometer. If the spectral intensity of the broadband source and the detector response are nearly constant over the range of interest, the signal output itself can be regarded a slit function for the spectrometer.

In a fixed grating spectrometer with multiple exits or array detectors, the slit function measurement is far more complicated compared with that for a scanning spectrometer. Spectral lines can be used to verify the dispersion characteristics at the exit plane but does not provide any direct information on the slit function. A broadband source offers no information on the slit function at all. It has been a common knowledge that a monochromatic source produced

with a pre-monochromator can be used for the slit function measurement. A narrow spectral beam is produced with a monochromator which has a narrow slit. This near monochromatic beam is used to illuminate the entrance slit of the spectrometer whose slit function is to be measured. But the flux level of this beam produced in this method is very low. To obtain a near monochromatic beam, the slit of the pre-monochromator has to be very narrow limiting the incoming flux. Also the output beam has to match the f-number of the spectrometer or overfill the spectrometer and to illuminate the entrance slit of the spectrometer uniformly. This requirement forces one to use a device like an integrating sphere. This approach reduces the available flux level. Thus, an accurate slit function measurement is not often possible. Also the slit function measured with this beam is a convolution of the true spectrometer slit function with the slit function of the pre-monochromator.

The OMI experiment aboard the EOS-Aura satellite has reported an improved light source for the slit function measurement¹. The light source is made of 150 Watts Xe arc and an Echelle grating spectrometer as a pre-monochromator. The Echelle grating blazes such that for the given combination of the entrance and exit slit the monochromator produces output lines in the grating orders from 54 to 100 which covers the OMI wavelength range from 250 nm to 500 nm. The spectral width of the output lines ranges from 0.028 nm to 0.053 nm. This is about 1/10 to 1/5 of the spectral resolution of OMI even though the monochromator can step in better than 0.005 nm. This experimental setup was benefited from the diffuser that is an internal component of OMI. Otherwise it would have needed an integrating sphere to provide a spatially uniform source which can fill the field-of-view of OMI. This approach is a significant improvement from the past approaches from the fact that the scanning can be reduced by a factor of upto 47. To obtain a true slit function of OMI, the measured slit function has to be deconvolved with the slit function of the monochromator.

With a tunable laser, the accuracy of the slit function can be improved greatly. The laser provides a strong spectral line source whose line width is very narrow. Therefore the measurement itself provides a direct slit function. TOMS is the first reported instrument whose slit function was measured with a tunable laser². The TOMS experiment requires accurate effective ozone absorption cross-sections to retrieve accurately the atmospheric ozone amount from the solar backscattered earth radiance measurement. The nominal spectral bandwidth of TOMS is 1 nm and the ozone absorption coefficient varies significantly within 1 nm. Therefore, the spectral bandpass shape (slit function) of TOMS has to be combined with the ozone absorption cross-sections to produce effective absorption cross-sections which are used for the automated data processing. The UV laser outputs for the TOMS wavelength range were obtained by doubling the tunable dye laser outputs. The doubling required a virtually continuous adjustment of doubling crystal manually for the wavelength scan. Three different dyes were used to cover the TOMS wavelength range of 308 nm – 360 nm. The TOMS slit function measurement with a tunable laser has produced quite accurate slit functions for TOMS. However, this measurement was very expensive and time consuming even though it had only six exit slits for one entrance slits.

4. APPLICATION OF A FOURIER TRANSFORM SPECTROMETER (FTS) FOR SLIT FUNCTION MEASUREMENTS

Fourier Transform Spectrometers (FTS) have been used in many applications in the infrared (IR) wavelength range since the computer technology has made Fourier spectroscopy practical. FTS has been used not only in analytical chemistry to measure chemical substances but also in metrology like filter transmission measurements as well as calibration of IR instruments. We explore the possibility of using a FTS to measure a spectrometer slit function. This approach can be extended to the visible and ultraviolet (UV) wavelength range especially for imaging spectrometer and multi-object spectrometer. This technique can be applied not only to a grating spectrometer but also to a wedge filter spectrometer.

Figure 2 shows a schematic of a typical setup for a filter transmission measurement using a FTS. Interferograms are measured in each case when the filter is in and out of the beam. The spectra are derived from the interferograms obtained with and without the filter. The transmission function of the filter is derived from the comparison of two spectra. The principle of the technique being explored is similar to that of this filter transmission measurement. Suppose that the spectrometer optics can be in and out in the beam between the spectrometer detector and FTS. Then, the spectrometer transmission can be measured, which is the slit function of the spectrometer. Since the spectrometer optics cannot be in and out in the beam path of FTS, a realistic and practical arrangement needs to be found.

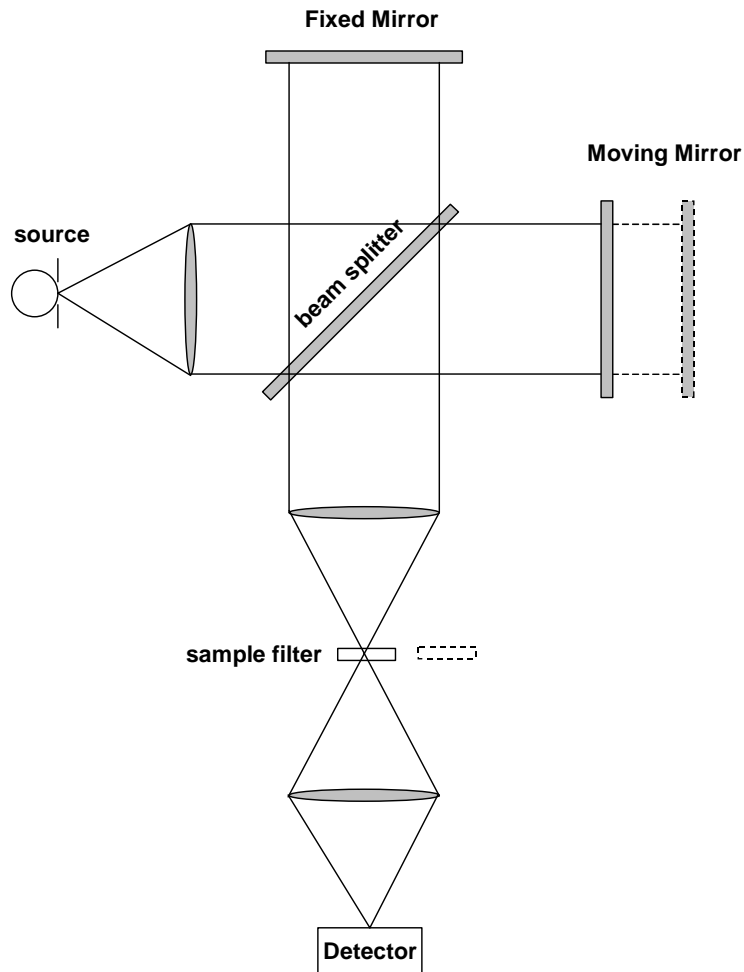


Figure 2. A schematic of a filter transmission measurement with a Fourier transform spectrometer. The interferograms are obtained with and without the filter in the beam path.

In the arrangement shown in Figure 3, the spectrometer entrance plane and a reference detector are placed in turn at the focal plane of the FTS and the interferograms are obtained. In Figure 3, a flip mirror is used to alternatively position the FTS focal plane on to the reference detector and the the spectrometer entrance plane. If the spectrometer has no magnification, a same kind of detector used for the spectrometer is preferred to be used as a reference detector. A spectral response comparison of the spectrometer detector to the reference detector can be made with a method shown in Reference 3 using FTS before the spectrometer detector is installed to the spectrometer. Once the relative spectral response of the spectrometer detector to the reference detector is known and the spectra are obtained from the conversions of the interferograms, the transmission of the spectrometer, which is a slit function of the spectrometer, can be calculated.

The above scenario is an ideal case of the measurement. The spectrometer may have a magnification or demagnification between the entrance slit and the exit slits. In this case, a true reference spectrum for each detector element for the spectrometer may not be obtained. In practice, the reference spectrum within the field-of-view of interest would not vary significantly in terms of the spectral shape. Also for the most of the occasions, the spectral response of the detector and the spectral distribution of the source are nearly constant so that the spectrum obtained by FTS using the spectrometer itself as an FTS detector can be considered as a slit function of the spectrometer.

For an accurate slit function measurement for a visible/UV imaging spectrometer, the following considerations should be made. Aliasing of the data should be avoided. According to the Nyquist principle, the critical sampling interval, Δx , should meet the following condition:

$$\Delta x = 1/2\nu_{\max}$$

where ν_{\max} is the maximum frequency to be measured in the spectrum. In the current technology, the optical path difference in an interferometer of FTS is commonly controlled with a He-Ne laser which has a wavelength of 632.8 nm. With an interferometric use of this laser and triggering the sampling at the zero signal crossing, the maximum bandwidth of the FTS using this He-Ne laser is $31,600 \text{ cm}^{-1}$.

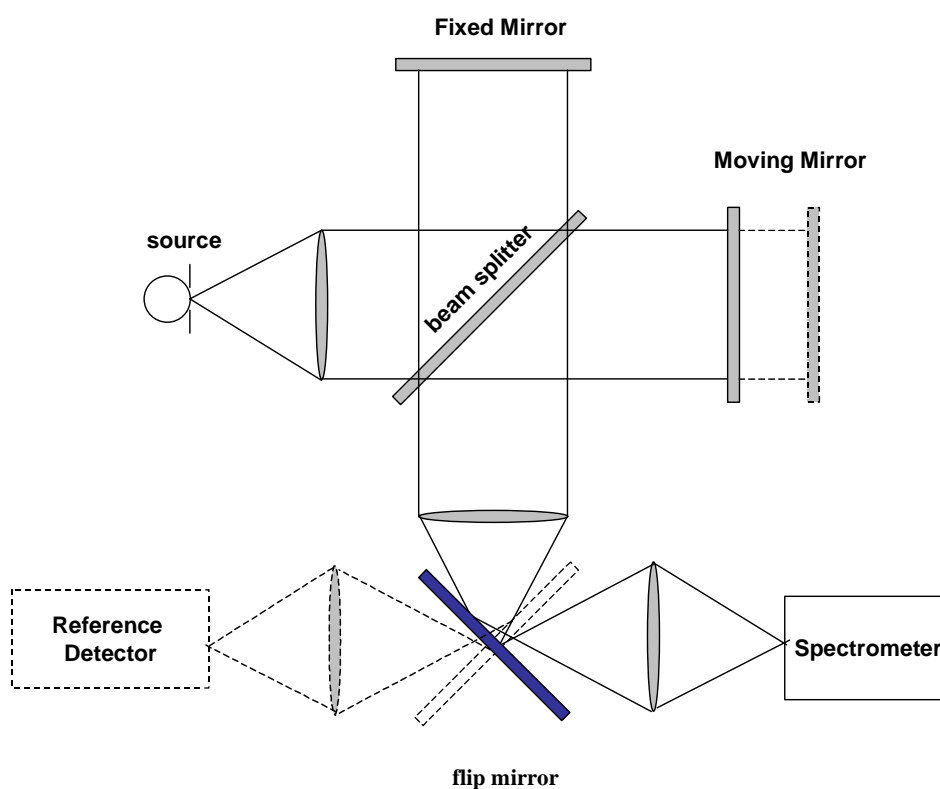


Figure 3. The FTS output is fed to a reference detector and a spectrometer alternatively with a flipping mirror.

The theoretical spectral resolution of FTS is $\sim 1.207/(2L)$ where L is the length of the total optical path difference. For a visible and UV application, the spectral resolution is more than adequate because of high value of the wave number.

Other cares need to be given when the FTS technique is applied to an extended source with a large field of regards for the slit function measurement. If FTS measures an extended source, two effects arise: 1) a shift of the measured wave number and 2) a broadening of spectral lines, so called the aperture broadening (Reference 4). The measured frequency and the true frequency have a following relation ship (Reference 4, Equation 6-38):

$$V_{\text{true}} = V_{\text{measured}} / (1 - \Omega/4\pi)$$

where Ω is a solid angle subtended to the extended source observed by FTS. The width of the broadened line is given by $V_{\text{true}} \Omega/4\pi$. If a source is off the axis of FTS by angle of θ , the optical path difference will be reduced by $\cos \theta$. In the astronomical applications, the angular size of the slit and the off axis angle are small and the above effects are negligible. However, in a low orbit earth observation, the field of view of the spectrometer can be large so that the frequency shift may be noticeable. Also the off axis angle can be significant so that the frequency should be determined accordingly.

In the experimental arrangement to measure the slit functions of a multi-object spectrograph or imaging spectrograph, the source has to provide a uniform field and a broad wavelength of interest. This source can be an integrating sphere with incandescent lamps or a blackbody source depending upon the wavelength range desired. A FTS should be capable of providing Nyquist sampling and a total optical path difference suitable for the desired resolution. Also a step scan type FTS should be used for the measurements where the detector readout takes a finite time.

5. SUMMARY

We present an approach for the spectrometer slit function measurements using a Fourier Transform Spectrometer instead of using a monochromatic source whose wavelength can be changed continuously as used in the past measurements. This approach fully utilizes the advantages of FTS overcoming the poor signal-to-noise ratio problem that the past measurements suffered from. This approach can also be applied to the visible and UV wavelength range. The inherent nature of FTS which requires a computer-assisted data processing can benefit to the measurements of the slit functions of imaging spectrometer and multi-object spectrograph where a combination of multiple entrance slits and the detector pixels generates numerous different slit functions.

6. REFERENCES

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